WATER RESOURCES RESEARCH GRANT PROPOSAL

Title: EROSION OF COHESIVE STREAMBEDS AND BANKS

Focus Categories: SED, G&G, FL

Keywords: WATERSHED MANAGEMENT, SOIL EROSION, STREAM SEDIMENTATION

Duration: 3/11/2000 through 2/28/2001

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Non-Federal Match: $40,000

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Congressional District: 5th - Washington

Statement of Critical Regional or State Water Problems:

Understanding of the mechanisms involved in the re-suspension processes of cohesive soils in natural channel systems remains an open case in water-related engineering disciplines. The main difficulty in characterizing these processes stems from the fact that cohesive sediment dynamics are controlled not only by physical forces (e.g., inertia, buoyancy, drag, lift, friction) but also by electrochemical forces (e.g., Van de Waals, electric double layer, etc.) (Scarlatos and Mehta 1993; Trofs 1997). A complete identification of the properties of cohesive sediments typically involves twenty-four parameters (Commission of the European Community 1993) and explains why the few studies referring to the erosion of cohesive sediment are site-specific rather than of a more fundamental nature.

This problem is further confounded in the Pacific Northwest region since a significant amount of the cohesive material found in stream beds and banks is contaminated, thus affecting the water quality and the ecology of the streams. USGS researchers have shown that maximum pesticide concentrations in Palouse River water are frequently associated with the highest suspended sediment concentrations (Wagner and Roberts 1998). The sorption of these contaminants in the structure of sediments could alter the degree of their cohesion and subsequently affect the rate of re-suspension occurring in a stream (Mehta et al. 1982). Contaminants reach the stream when soils from surrounding watersheds are eroded. In the dry land wheat-growing region of the Palouse, about 80% to 90% of the annual upland erosion occurs in the winter months when the soil has little crop cover, since grain is seeded late in the Fall or early in the Spring (Steward et al. 1975). The runoff and snowmelt that occurs in early spring periods cause the transport of this material into rivers. Consequently, these contaminated materials become part of the river sediment texture.

Many of these contaminated sediments are buried in streams at depths of up to several feet (USGS circular 1165). A major question is whether these buried sediments and contaminants can be exposed and eroded during floods. In order to quantitatively understand and predict the transport and fate of sediments during large floods on rivers, the re-suspension and erosion properties of sediments at high bed shear stresses, on the order of 1000 dynes/cm^2, are needed (i.e., current cohesive sediment transport models are applicable for applied shear stress values up to 50 dynes/cm^2) (DePinto et al. 1994). Since most of the contaminants are associated with fine-grained sediments, knowledge of the source and properties of these fine-grained sediments is essential.

The principal water sediment-related problems addressed in this research will provide better understanding of the turbulent flow mechanisms involved in the re-suspension process of cohesive sediment and will investigate the role of degree of soil consolidation on the re-suspension process with changing flow conditions.

Statement of Results and/or Benefits

This research will improve our ability to predict the re-suspension processes of cohesive materials during different flow conditions. It will also provide us with methods of predicting accurately the quantity of cohesive sediment transported for flow events ranging from near-threshold conditions to extreme floods. For the first time the erosion rate of cohesive materials will be calculated as a function of the "consolidation age" of soils, and applied bed shear stresses greater than 50 dynes/cm^2. These results will be used to improve the design of river-related works such as bank stability problems in cohesive soils, cohesive sediment lateral migration in sharp bends, bridge pier scour in cohesive soils, and thus minimize the potentially detrimental effects on stream ecology.

Results will be published in the refereed literature (e.g., Journal of Hydraulic Engineering ASCE, Water Resources Research) and will be presented in a national Water Resources conference (AGU). The proposed investigation will provide support for one M.S. student and at least one undergraduate student. The students will be involved in all aspects of the project: field data collection and analysis, laboratory work, and analytic work. In addition to the work directly supported by the grant, the Rock Creek field site will be a “gathering place” for undergraduate and graduate classes. During these meetings, demonstrations and hands-on sessions will be provided to students, inspiring them to pursue this field for their emphasis or for graduate work. Finally, the co-Principal Investigators will be cooperating and collaborating to support the career of a young faculty member. It is expected that this collaborative effort will be the start of a much-needed long-term research program related to the transport and fate of contaminated-cohesive soils. The findings of this research will provide the foundation for follow-up submissions to major funding sources.

Nature, Scope and Objectives of Research

The treatment of cohesive sediment is one of the last elements of sediment transport that is addressed almost entirely from an empirical standpoint. At present, no general quantitative theory for cohesive sediment re-suspension properties is available, and field and laboratory experiments are needed to determine these properties (McNeil et al. 1996; Zreik et al. 1998; Ravens and Gschwend 1999).

The objectives of this research are:

1. To improve our understanding of the basic mechanisms involved in the re-suspension process of cohesive sediment, and examine the role of different parameters (e.g., degree of consolidation of soils) on the re-suspension process with changing flow conditions. For the first time, the erosion and resuspension rate of fine sediment will be determined by accounting for the role of the near-bed turbulence structures (i.e., turbulent bursts). Nowadays, it is believed that the occurrence of turbulent bursts is responsible for the entrainment of sediment in natural streams (Nelson et al. 1995). Turbulence will be accounted by measuring the geometric characteristics of bursts and frequency of their occurrence (Papanicolaou et al. 1999a; Papanicolaou et al. 1999b). Subsequently, sediment entrainment formulas to predict the erosion rate of sediment as function of soil properties and the applied turbulent stress are expected to be obtained. These formulas are very much needed for sediment erosion prediction, especially in the occurrence of floods because most of the existing models are limited to low flow conditions.

2. To develop of a rational framework for monitoring and evaluating (M&E) cohesive-sediment erosion due to the erosive power of water. The use of a particulate calcium 13-carbonate to the identification of sediment sources and the characterization and identification of depth of erosion will be considered throughout the course of this investigation. Calcium-13 carbonate particulate has been successfully used in the past to identify the origin of soils transported into streams (e.g., Peart 1993).

This research consists of two components, field and laboratory. Field data should be collected first in order to perform the laboratory experiments. The field data will be coupled with the laboratory to provide a complete description of the re-suspension process.

Field data will be collected at Rock Creek watershed, located about 60 miles northwest of the Washington State University (WSU) campus near Spokane, WA. Rock Creek is overlain by mostly brown clay silt alluvium deposits (silt loess). Field measurements at

Rock Creek will enhance our understanding of sediment and contaminant transport in rivers, since the data will provide useful information about the properties of the undisturbed sediment and their correlation to the erosion rate (laboratory experiments by their very nature deal with disturbed sediment). By using Calcium 13 (13-C) as a tracer (found in the compound of a calcium carbonate), the origin of the re-suspended material will be identified.

Laboratory tests, the second component of this study, will take place in Albrook Hydraulic Laboratory of WSU and will simulate the erosion process in Rock Creek for reconstructed and aged cohesive sediments under extreme flow conditions. Data corresponding to flood conditions are difficult to obtain from field studies, and thus, the performance of these experiments will be a vital component of this research effort as this information is not currently available in the literature. The laboratory data will provide a linkage between the characteristics of turbulence (e.g., frequency of occurrence, and magnitude) with the entrainment of reconstructed sediment employed under various "consolidation ages".

By coupling the results from laboratory and field tests, the complete re-suspension properties of in-situ surficial sediments will be approximately determined and an erosion formula that accounts for episodic turbulent-flow events will be developed. To our knowledge, this will be the first combined analysis of laboratory and field measurements. These two components will be completed in a total of 12 months, which includes one sampling season at Rock Creek and a period of eight months to perform and analyze the flume experiments.

It is expected that this M&E framework can be used to study the existing erosion problems within the region and yield the development of sediment stabilization techniques that could minimize adverse effects on stream ecology. The audience for the final product of this research includes federal, state and local agencies as well as consulting engineers involved in all aspects of transport of contaminated sediments, bridge safety and foundation scouring problems. Management decisions and budget allocations will also be greatly facilitated by this research since priorities associated with M&E of water quality in natural streams will be more identifiable. The findings of this research will provide the basis for follow-up submissions to major funding sources.

Methods, Procedures, and Facilities

No investigation has successfully isolated the role of soil properties and flow mechanisms on the cohesive sediment re-suspension process. This will be achieved here by coupling field measurements (at Rock Creek) with laboratory tests (at Washington State University). Field measurements will include flow data (e.g., depth-averaged velocities, turbulent intensities), soil data (e.g., soil cores), identification of soil sources (e.g., use of a particulate calcium carbonate), and erosion rates (e.g., bed load or suspended load) in cross-sections.

Specifically, for the first time the effects of streambank erosion on the transport cycle of cohesive material in a stream will be considered. For this purpose, particulate calcium carbonate will be distributed along the banks of Rock Creek following the methodology of Peart (1993) and Lobb (personal communication, 1999). This is to distinguish the origin of soil found within the Creek. It is expected that a portion of the bank material that is eroded will be deposited atop the river bed while the lighter grains will become part of the stream suspending material. During low flow conditions, this material will ultimately reach the riverbed, but carried downstream during high flow conditions. The transport of cohesive sediment is typically characterized by two threshold conditions, one, for newly deposited sediment and the other for those that have undergone some degree of consolidation (Scarlatos and Mehta 1993). Although the literature does not often distinguish between these conditions very clearly, in the present study the two threshold conditions will be identified by measuring the bulk properties of sediment as function of depth for a sufficient vertical resolution. To provide meaningful field data, field survey and flow measurements in Rock Creek will include three monitored sections. The field measurements will be performed during high and low flow seasons (March and August respectively).

While the advantage of field measurements is the description of the re-suspension properties of sediments as they are in the field (i.e. undisturbed), the disadvantage is that they provide no information on the consolidation history of the cohesive sediments and the effects of soil compaction on sediment re-suspension. This suggests that laboratory experiments of reconstructed sediments need to be coupled with field tests to adequately describe the complete re-suspension properties of cohesive soils. Historically, flumes (straight or annular) have been employed to monitor sediment erosion in the laboratory (e.g., Partheniades and Kennedy 1966). Use of a flume allows the performance of erosion tests and yields data on erosion processes without having to consider other complicating sediment transport processes that would be present under natural conditions.

In particular, laboratory experiments will determine the parameters on which re-suspension depends and the quantitative effects of these parameters on re-suspension. In the proposed investigation, batch sedimentation tests will be performed to study the consolidation history of the reconstructed brown clay sediment collected from Rock Creek. These tests will be complemented with the use of a computer program employed to predict cohesive sediment consolidation history under various initial slurry concentrations. In turn, the reconstructed soil will be placed atop of the flume bed to perform several erosion tests under various flow conditions (simulating low to high flow conditions).

The Hydraulic and Hydrogechemistry labs at WSU, are equipped with the instruments that are needed to conduct this research, a mass spectrometer for carbonate analysis, a bed load sampler and sedimeter to measure bed load and suspended load respectively, a state-of-the-art Laser Doppler Velocimeter, a Vibracoring head, an Acoustic Doppler Velocimeter, and a velocity micropropeller, Swoffer. The particulate calcium carbonate compound will be purchased from the Cambridge Isotope Laboratories, MA (www.Isotope.com). Cost for the purchase of the calcium carbonate and use of the spectrometer is included under budget/supplies.

To meet the objectives of this investigation the following tasks are to be undertaken:

<u>Task 1</u>: Perform field experiments to identify the origin of the transported material within Rock Creek, and determine the role of material properties and flow mechanisms on the cohesive sediment re-suspension process.

<u>Task 2:</u> Perform laboratory measurements to examine the erosion process of reconstructed sediment under various consolidation ages and isolate the role of turbulence on sediment re-suspension.

<u>Task 3</u>: Develop a cohesive sediment erosion model to predict the erosion rate of sediment as function of soil properties (e.g. bulk density, soil moisture), and the applied bed shear stress by the flow.

The timeline of the proposed activities is shown in table 1. Each task is considered in detail below.

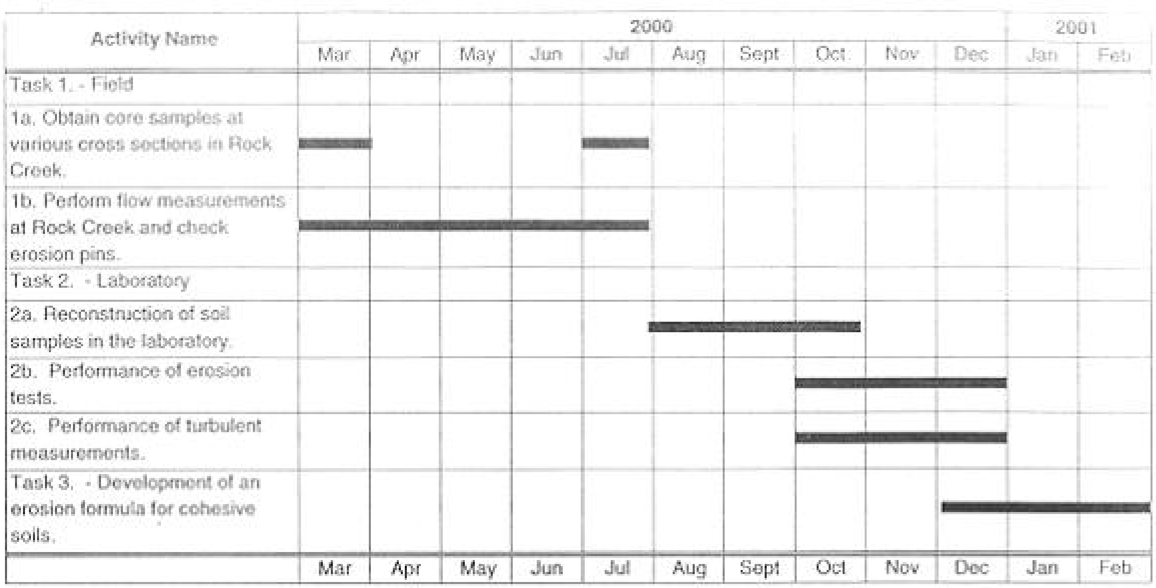

Table 1. Timeline of the proposed activities.

<u>Task 1:</u> Field measurements.

This task is subdivided into the following subtasks:

<u>Subtask 1a</u>. Obtain core samples at three cross sections in Rock Creek.

Core samples will be collected at various sampling locations along three specified cross sections in Rock Creek during the first period of this project. To do so, sediment core cylinders 2 m long by 10 cm outer diameter will be used. The collected sediment will be reconstructed and used in the laboratory, to determine soil consolidation age, soil properties, and soil erosion strength under a given applied stress (see subtask 2b). For locations with newly deposited soils, the soil samples will be obtained by attaching the sediment core cylinders to a long pole. For sediments that are more compact and/or deeper waters, soil samples will be obtained with the use of a Vibracoring head (this equipment is available to the Pi's of this project). During sampling, the bottom of the core will be sealed before raising it out of the water.

Subtask 1b: Perform flow measurements at Rock Creek and check erosion pins.

Several flow measurements will be performed in Rock Creek during different periods (table 1). The aim is to “map” the velocity flow field within the sharp bends of Rock Creek and evaluate the role of turbulence on cohesive sediment re-suspension process. According to Nelson et al. (1995) and Papanicolaou et al. (1999a, 1999b) highly turbulent energetic events, known as bursts, are capable of causing massive bed failure (i.e. mass erosion) in cohesive bed streams and increase the likelihood that contaminated sediments buried and effectively sequestered from the food chain will be exposed to the flow and eroded. Flow measurements will be performed by means of a three–dimensional turbulence-resolving mechanical current metering system (Swoffer) and a SonTek Acoustic Doppler Velocimeter (ADV) (both instruments are available to the Pi's of this project).

Field measurements in this subtask will include also surveying of the three channel cross sections (to monitor the variations that occur in Rock Creek bed elevation), identifying bankfull elevation, and measuring water surface slope. To measure the material eroded from the banks, erosion pins will be installed at three specified cross-sections in Rock Creek. These pins, which are typically metal rods of 20 mm diameter and 1200 mm in length, will be inserted horizontally into the bank, leaving only a small fraction exposed. Bank retreat will be estimated from the progressive amount of pin exposure, measured with a ruler or calipers. The installation of the pins will take place in early March 2000, while the erosion process will be monitored with the help of a graduate (Rob Hilldale) and an undergraduate student (Kyle Strom) during different periods of the study.

The flow and bank erosion data will be complemented with bed load and suspended load measurements. The bed load and suspended load measurements will be performed at the same locations and in sequence of the turbulent flow measurements in order to provide a linkage between flow and sediment flux. For this purpose, the time series plots for sediment flux and turbulent stresses will be analyzed to identify if there is time lag between high peak flows and sediment fluxes. Turbulence spectra will be employed to obtain spatial information about the structure of turbulent bursts. According to Cao (1997), the area (i.e., spatial characteristic) of a turbulent burst and its frequency (i.e., temporal characteristic) affect the rate of sediment transported by the flow. Based on these recent findings the Pi's will estimate the river turbulence characteristics and their relationship to basic hydraulic characteristics. Relations that correlate the bursting area and frequency with sediment flux will be developed.

Bed load sampling will be performed by using a BL-84 bed load sampler (that is available to the Pi's of this project). The BL-84 has the same opening and wall thickness as the Helley-Smith sampler (this is the most common sampler) but it fits more easily in the channel bottom because the reduced flare is less intrusive among large grains. BL-84 is less disruptive to the flow and is recommended by the USGS (Nelson 1999, personal communication).

Suspended load will be measured by means of a sedimeter. The sedimeter is a state-of-the-art instrument for measuring suspended load (www.hydroconsult.se/sedimeter.html). Sedimeter measures erosion and accumulation of sediments with a resolution and accuracy down to 0.1 mm and for water depths up to 50 m. The sensor is a rod 20 mm diameter that is immersed into the bottom. Measurements are made with infra-red back-scatter detectors, to minimize the influence of ambient light. The sedimeter data are stored in a logger and retrieved by the help of a computer. The sedimeter device is available to the Pi's of this study.

Calcium carbonate in the form of solid particles enriched with the tracer calcium-13 will be distributed along the banks of Rock Creek following the methodology of Peart (1993) and Lobb (personal communication, 1999). This is to distinguish between soil grains that are already deposited and consolidated at the Rock Creek bed with those that are transported within the stream from the surrounding stream corridor. According to Peart (1993), the application of calcium carbonate is straightforward. Access to the field location does not require any special permit and difficulties of using the above technique are not anticipated (instead use of radionuclides as tracers will pose several problems). Sediment samples will be taken at least once every 15 days after the application of the isotopes (from March to August of 2000) to ensure identification of the soil source (Nagle 1997). Sediment samples will be taken either as suspended sediments or from the Creeks bottoms. According to Hasholt (1988) and Peart (1993) the use of stable isotope tracers is the most reliable available technique for identifying sediment sources during erosion tests. The error of this new technique used in catchment-hydrology applications is less than 10% (Nagle 1997).

Task 2: Laboratory measurements.

<u>*Subtask 2a*</u>*: Study of the consolidation history of soil samples.*

To reconstruct sediments of various consolidation ages for the erosion tests (task 2), the soil samples collected from Rock Creek will be mixed at different initial concentrations with water to form slurries. The different initial volume fraction of solids slurries will then poured in batch sedimentation cylinders and allowed to consolidate for at least 2 to 60 days (Diplas and Papanicolaou 1997). Two different types of sediment layers can be prepared in this manner. The first is a stratified layer in which the slurry is poured into the batch cylinder and left undisturbed without any further mixing. This sediment layer simulates a large flow event in which a large amount of sediment is deposited in a short period. The second is a well-mixed layer in which the slurry is allowed to settle for several days, so that the water content of the slurry is reduced. This type of reconstructed sediment layer simulates a series of small flow events that deposit small amounts of the same kind of sediment (Zreik et al 1998). The soil properties of the formed sediment layers will be measured by analyzing small soil samples. These samples will be obtained from the ports that typically are located at the side of the batch cylinders at a different height along the cylinder side. The bulk density will be calculated according to the method of Hakansen and Jansson (1983). The consolidation program CONSOL, written in Fortran language and developed by Papanicolaou and Diplas (1999), will provide the variation of the sediment density profile with time. The above information will be incorporated in Task 3 to develop a formula that predicts erosion of cohesive soils for a wide range of flow conditions and degree of consolidation.

Subtask 2b. The objective is to simulate the erosion process in Rock Creek for reconstructed and aged to various times cohesive sediments and under extreme flow conditions.

Several cohesive erosion experiments have been performed in the laboratory in annular flumes and shakers (e.g., Fukuda and Lick 1980), only at shear stresses less than 10 dynes/cm^2 (DePinto et al. 1994; Trofs 1997; Zreik et al. 1998). The construction of a "sedflume" by McNeil et al. (1997) allowed the performance of erosion tests for applied shear stresses up to 100 dynes/cm^2. Despite this considerable improvement, even tests performed in a "sedflume" do not represent the flow conditions typically encountered in natural streams (Zreik et al. 1998). Moreover, "sedflumes" due to their design limitations do not allow observations or measurements to be made that will elucidate the flow mechanisms responsible for cohesive sediment erosion (Zreik et al. 1998).

In the present study the above limitations will be removed by performing various erosion tests in a straight water re-circulating flume located in WSU for applied bed shear stresses greater than 1 KPa (or 1000 dynes/cm^2). The flume model study will focus on the simulation of the erosion process in Rock Creek and will provide useful information for a wide range of flows. These experiments will be supplemented with the field investigation at Rock Creek (subtasks 1a and 1b) and with the consolidation data generated at the hydraulic laboratory (subtask 2a).

The tests will be performed in a water re-circulating flume 75 ft long, 3 ft wide, and 3 ft deep. Sufficient flow (60 cfs) to generate applied shear stresses greater than 1 KPa is available from pumps drawing water from the sub-floor sump. The issues examined as part of the experimental design process are: scaling and construction of the Rock Creek model, sediment placement in the model and thickness of the clay material that will used, methods to monitor sediment erosion, and flow measurement techniques. The model will be scaled according to the dynamic similarity laws for movable beds (Zreik et al. 1998) and will simulate a section of Rock Creek (the surveying information from subtask 1b will be employed here). The properties of the reconstructed clay silt material used for the model will be similar mechanically and chemically to that found in Rock Creek. Two types of sediment layers will be placed in the model (described in subtask 2a). A total of seven tests will be carried out with the bed age varying between 2 and 60 days. The thickness of the sediment layer will be at least 1.5 ft to examine the role of consolidation to the re-entrainment of sediment (Zreik et al. 1998). The velocity measurements will be obtained with the use of a state-of-the-art Laser Doppler Velocimetry (LDV). The LDV measurements will be correlated with the entrainment of cohesive sediment to isolate the flow events causing erosion. According to Wang and Larsen (1995), the re-suspension of clays does not impose significant problems for Laser measurements made in the outer flow region. Analysis of the flow data will provide the turbulence spectra and scales of velocity fluctuations, which will be employed to obtain information on temporal and spatial scales of turbulent structures. During a test, the applied shear stress will increase incrementally according to the method of McNeill et al. (1997). At the end of each stress increment, the concentration measurements will be obtained accurately by means of a sedimeter (described in subtask 1b) and the erosion rates will be calculated by means of the method outlined by Mehta et al. (1982). In the present study, parameters such as the water salinity and temperature will not be considered.

<u>Task 3</u>. The data that will be collected in tasks 1 and 2 will serve as a basis to provide a correlation formula among cohesive sediment characteristics and erosion rate. This correlation formula will provide definite advantages comparatively to the existing ones since they will predict the erosion and re-suspension rate of cohesive sediment for extreme flow conditions and by taking into account the consolidation history of soils and the near-bed turbulence characteristics. For the first time, the effects of the soil properties of cohesive materials will be incorporated into the formulation of an erosion model. The formula that will be constructed here based on the laboratory data will be calibrated by using the field data of subtasks 1a and 1b.

Related Research

Recent reviews of the state of knowledge of cohesive sediment pertinent to erosion (e.g., Trofs 1997) show that there is little agreement on the best parameterization of the erosion rate of cohesive sediment and it seems that not a great deal of progress has been achieved since then. The existing erosion models typically do not account for the deposition and consolidation effects. Most of these models also assume a linear variation between the erosion rate and the bed shear stress. However, the studies of Fukuda and Lick (1980) and Gailani et al. (1991) have indicated that an exponential relationship between the erosion rate and the bed shear stress may be more appropriate. According to Gailani et al. (1991), the erosion rate is governed by a power law that relates the total amount of sediment re-suspended by the flow to the effective stress. Specifically, the amount of sediment eroded from a cohesive bed is given by (Gailani et al. 1991)

$$\varepsilon = \frac{a_o}{T_d^m}\left(\frac{\tau_b - \tau_{cr}}{\tau_{cr}}\right)^n, \tau_b \geq \tau_{cr}$$

Where e= net mass of re-suspended sediment per unit surface area (mg/cm^2); a_0 = site-specific constant, T_d= time after deposition in days; m and n are dependent upon the deposition environment; and t_{cr} = effective critical shear stress. The above equation is not appropriate when the applied shear stresses are greater than about 20 dynes/cm^2. Recently, McNeil et al. (1997) expressed the need to improve the techniques used to measure the bulk properties of cohesive sediments. They suggested that even now it is difficult to obtain satisfactory relations that express the dependence of erosion rates on soil properties. Possible reasons for this are: a. The bulk properties as a function of depth have not been measured with sufficient vertical resolution, and b. quantitative information on additional bulk properties (e.g. amounts of oil and grease) are not available in the literature. These suggestions will be taken into consideration in the proposed study. For the first time the erosion rate of cohesive materials will be calculated as a function of the "consolidation age" of soils, the contents of heavy metals found in the soil texture, and applied bed shear stresses greater than 100 dynes/cm^2.

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